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Early Lake Ontogeny following Neoglacial Ice Recession at Glacier Bay, Alaska

by

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Abstract

This study explores the environmental forces controlling lake ontogeny at Glacier Bay as a model for early Holocene lake evolution in north temperate lakes worldwide. Long-term chemical and biological changes in lakes are investigated with two complementary research strategies: (1) limnological conditions are compared among 32 lakes of known age and in different stages of primary catchment succession and (2) sediment cores from these same lakes are analyzed stratigraphically for fossil diatoms to ascertain developmental trends in pH, alkalinity, algal composition, and trophic status at individual sites.

Trends in water chemistry inferred from the chronosequence approach include a progressive loss of alkalinity and dilution of surface waters, an increase in apparent color from organic acids, and a decline in pH. Because of considerable scatter in the chronosequence data, these changes are not apparent until several hundred years after deglaciation. Preliminary observations of biotic trends include an apparent succession of higher aquatic plants mediated by alkalinity changes and a rapid diversification of the diatom flora associated with a proliferation of new growth substrates, particularly macrophytes.

Several hypotheses concerning early postglacial land/water interactions are supported by these results, including (a) the progressive leaching of catchment soils makes lakes more dilute and acidic over time, (b) peat growth and regional paludification impede internal soil drainage and groundwater recharge, causing dilution and eventual dystrophication of surface waters, and (c) hydrologic and geologic differences among sites act to control the rates and direction of limnological change.

KEY WORDS: Paleolimnology, hydrology, lake chronosequence, succession, diatom stratigraphy, water chemistry, dystrophication.

Lake ontogeny, as an ordered progression of trophic states resulting from maturation of the landscape, has been viewed by some as a trend towards eutrophy and by others as an opposite trend towards oligotrophy. The more widely held view within ecology, that evolved lakes are more productive, is confounded by the process of cultural eutrophication. Nevertheless, many paleolimnological studies have noted biotic changes indicating an early postglacial increase in lake productivity (e.g., Davis et al. 1985). Likewise, stratigraphic evidence for progressive oliotrophication, in which lakes become more acid and unproductive over time, is equally strong (e.g., Whitehead et al. 1986). Such divergent results clearly suggest that lake ontogeny is a process in which trajectories and rates depend on initial geologic and climatic conditions as well as subsequent changes in vegetation, soils, and hydrology.

In order to explore more directly the environmental forces controlling lake development, we are presently studying a series of recently formed lakes along a deglaciation chronosequence in Glacier Bay National Park. We are investigating the early stages of lake ontogeny in relation to primary succession in vegetation and soils following more than 1,000 years of Neoglacial ice recession. This study emphasizes changes in water chemistry, primary production and phytoplankton composition, and the influence of catchment lithology and hydrology in regulating material inputs to lakes. We wish to test several hypotheses that have been generated by previous paleolimnological studies concerning these land and water interactions:

(1) There is a progressive decrease in the export of dissolved solids from catchment to lake waters associated with the leaching of soluble minerals from upper soil horizons. Lakes eventually become more acidic over time.
(2) Increased nutrient inputs, particularly N and P, associated with early pedogenesis may cause an initial increase in primary production and a shift from benthic

to planktonic algal forms. This productivity increase may be short-lived as the pool of 3 primary mineral phosphorus is subsequently depleted in the upper solum.

(3) Hydrologic and lithologic differences among sites act to control initial water chemistry and the rate of limnological change associated with terrestrial primary succession.

(4) In environments with high net precipitation, the development of histic (peaty) soils impedes internal soil drainage and leads to the increased export of humic materials and the widespread dystrophication of surface waters.

Our focus on the early phases of lake development provides an important analogue to events that occurred on a continental scale thousands of years ago. The period shortly following continental deglaciation was one of dynamic environmental change associated with climatic warning and the re-invasion of plants and animals. All paleolimnological evidence thus far points to an equally rapid transformation of aquatic environments associated with terrestrial change.

The problem of early lake ontogeny has been attacked with two independent and complementary research strategies: (1) limnological conditions are being compared among 32 lakes of known age and in different stages of primary catchment succession and (2) sediment cores from a selection of these same lakes are being analyzed stratigraphically for fossil diatoms and algal pigments to ascertain developmental trends in pH, alkalinity, and algal compositions at individual sites. In the chronosequence approach, limnological change is inferred from the comparison of younger and older sites, presupposing that the primary difference among lakes is age since formation. Of course, lakes may differ in other important respects, such as the geological and hydrologic setting, which might add considerable variation to any chronological pattern. If one takes into account such watershed differences, however, the divergence of certain lakes from an otherwise dominant trend should be instructive.

The paleolimnological approach, on the other hand, eliminates the uncertainty of inter-lake comparison by following the historical development of a single site, but it does so at the expense of direct limnological observation. Difficulties arise because temporal resolution from sediment stratigraphy is often poor, modern analogues are often lacking for early postglacial environments, and reliable calibrations of sedimentary components required for quantitative reconstructions exist for only a few parameters, such as pH. Despite such limitations, paleolimnology can serve to verify processes inferred from a representative series of lakes taken at a single point in time. A combination of comparative limnology and core work as undertaken here is thus synergistic in that it complements the fine resolution of direct observation with the certainty of stratigraphic change.

Study Sites

The 32 lakes in this study are situated at low elevation (< 200m) in small primary catchments receiving no drainage from other lakes or major streams; most are small (3-16 ha) and moderately deep (Z_{max}=3-18 m). More than half are located within Glacier Bay proper and as such are no older than the Bartlett Cove moraine (ca. 200 years). Eleven of the youngest lakes, found along Muir and Wachusett Inlets, have catchments in early stages of terrestrial succession. Another seven sites are situated in the spruce/hemlock forests of the lower bay, while three lakes are in transitional areas at mid-bay. Eleven additional lakes, which extend the chronosequence to older surfaces, are located near Lituya Bay (350-400 years), Taylor Bay (1,200-2,000 years), the terminus of the LaPerouse and Dagelet Glaciers (ca. 2,000 years), and on Pleasant Island (14,000 years). The vegetation surrounding these lakes ranges from hemlock/spruce forest at Lituya Bay to an increasing prevalence of muskeg in the older catchments.

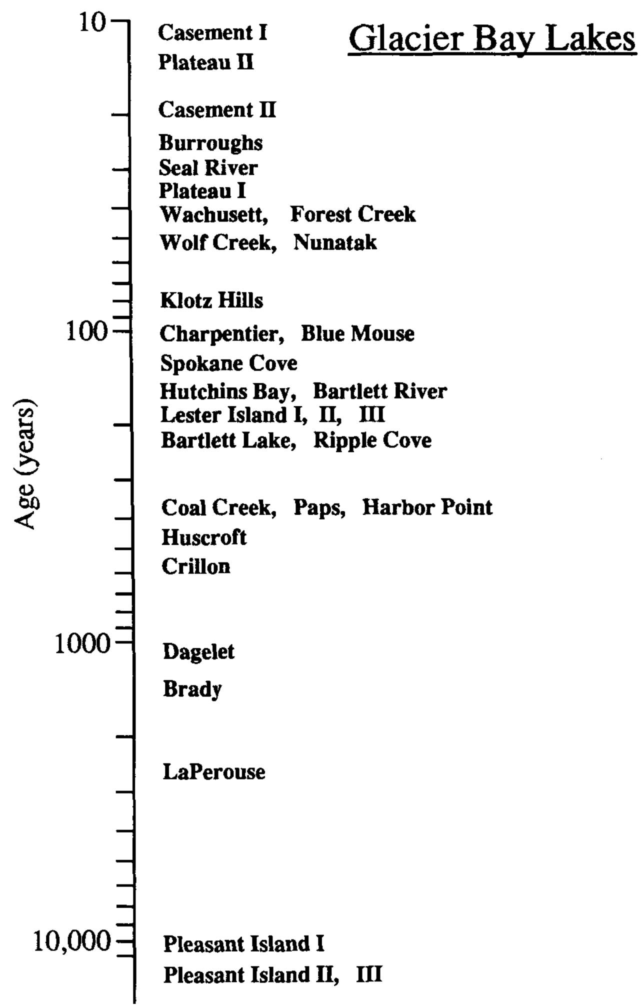

Fig. 1. Age distribution of study lakes at Glacier Bay.

The exact age of the early Neoglacial sites is subject to verification by radiocarbon dating (presently in progress). The late Wisconsinan deglaciation of Pleasant Island is already known from ^{14}C dating at one of our sites. The age distribution of the study lakes is shown in Figure 1.

Methods

In the course of this study, all lakes will have been sampled at least three times (July 1987, Sept. 1988--already completed, and May 1989) to assess seasonal and year-to-year variability in limnological conditions; these results are supplemented for many of the sites by preliminary data from September 1983, 1984, and June-July 1986. At each visit, a temperature profile of the lake is recorded, epilimnetic and hypolimnetic water samples are taken, and collections of zooplankton, phytoplankton, and attached algae are made. Laboratory analyses of field collections include major cations and anions, nutrients (total-P, total-N, and dissolved-Si), apparent color, conductivity, chlorophyll, and dissolved organic carbon (DOC). In addition, we have surveyed the composition and abundance of macrophytes in each lake, mapped basin morphometry by recording depth meter, and collected unweathered till samples from soil pits in each catchment to assess basin lithology. We have also cored the sediments of all 32 lakes with a piston corer operated by rigid drive rods from the lake surface. Hydrological work associated with this project is described by J. Almendinger in this volume.

Results

Chronosequence

A summary of epilimnetic water chemistry from July 1987 (Fig. 2) shows a wide range of ion concentrations for lakes in Glacier Bay National Park (0.1-5 meq/L). The more concentrated lakes with ion sums >1 meq/L are dominated by Ca^{+2} and HCO_3^- ions, whereas the more dilute lakes have a mixed ionic composition with Na^+ and Cl^- in greater proportion. This pattern results from the predominance of dilute lakes along the outer coast where seaspray is an important component of precipitation. Earlier results from 12 of these sites sampled in 1983, 17 sampled in 1984, and 8 sampled in 1986 are very similar. Chlorophyll-a concentrations for these same sampling periods are generally below 2 or 3 μg/L, and total phosphorus is less than 10 ppm, implying highly oligotrophic conditions in most lakes.

Although the data are as yet incomplete, a number of limnological parameters exhibit striking trends with lake age

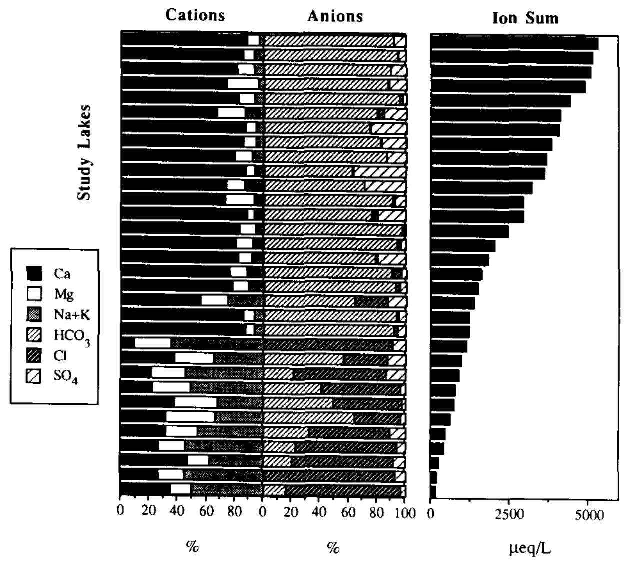

Fig. 2. Major ion chemistry of epilimnetic water samples taken in July 1987; cations and anions expressed as percentages of their respective sums in μg/L; ion sum = cations + anions.

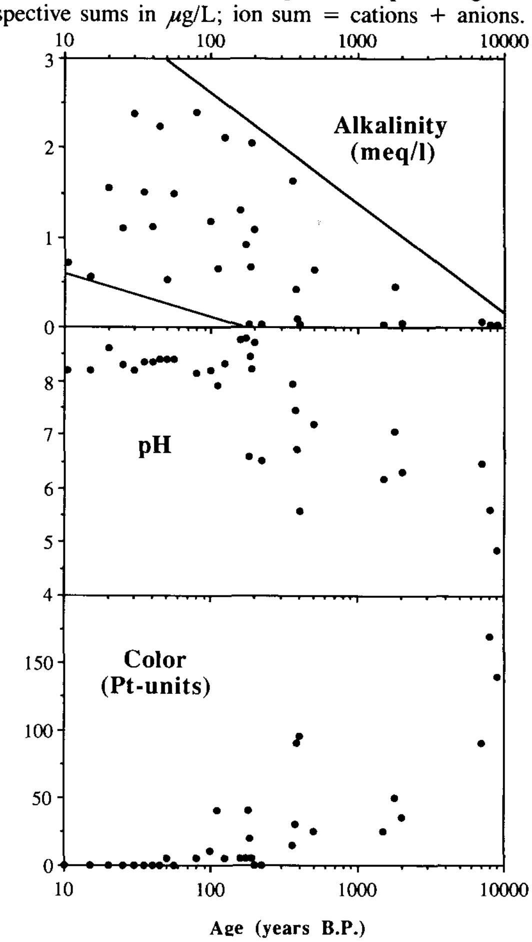

Fig. 3. Relationship between surface age and epilimnetic alkalinity, pH, and apparent color for 32 lakes sampled in July 1987.

that suggest the processes hypothesized previously for early lake ontogeny. All major cations and all anions except Cl^- show declining values along the chronosequence of sites from youngest to oldest. The general trend is illustrated here (Fig. 3) by data for alkalinity (primarily HCO_3^-). While there is a good deal of scatter in the data for any particular time slice, there are clearly no "old" lakes with high alkalinity, and conversely no "young" lakes with low alkalinity. Other solutes show more or less variance in this pattern, while certain sites are consistent outliers for all ions. Notable trends are also evident in pH and apparent color, a relative measure of organic acid content (Fig. 3). Epilimnetic pH is uniformly high (>8.0) for lakes less than 200 years old but shows a declining pattern with lake age among older sites, beginning with two lakes in the Bartlett Cove area. This pH trend reflects the greater carbonate buffering of the younger lakes (high alkalinities) and the increasing concentration of organic acids (as illustrated by apparent color) in the older lakes.

The scatter in the above trends illustrates the individualistic nature of lakes and underscores the difficulty in using chronosequence to infer universal patterns in lake ontogeny. In some cases, the variability among lakes of similar age can be ascribed to differences in geologic setting, where certain rock types contribute a greater flux of solutes to a lake than do others. For example, three lakes along the lower reaches of Wachusett Inlet exhibit SO_4^{-2} concentrations of 30-40 ppm, an order of magnitude higher than the mean for all other lakes in the data set (3.1 $\pm$ 4.2 ppm, $\pm$ 1σ). This sulfate "anomaly" probably results from weathering of locally abundant sulfate or sulfide minerals in the watersheds of these lakes.

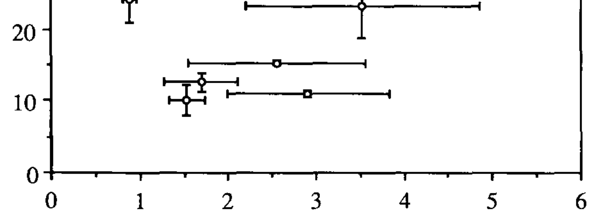

Fig. 4. Relationship between the carbonate content of unweathered soil samples and epilimnetic Ca^{+2} concentrations at study sites in the Muir Inlet area; error bars = $\pm$ 1σ, representing 2-3 soil pits and 2-4 water samples (from consecutive years).

In most cases, however, catchment lithology explains little of the variance in lake chemistry, as shown by a comparison of soil and water chemistry for sites in the Muir Inlet area (Fig. 4). Among this subset of our youngest lakes (all less than 80 years old), there is no discernible relationship between the carbonate content of unweathered soil samples and lakewater Ca^{+2}. Such variability among lakes of similar age can be ascribed instead to differences in hydrologic setting and the relative contributions of groundwater, surface flow, and direct precipitation to the lacustrine water budget. Groundwater (including stream flow) typically carries a much higher load of dissolved solids than does runoff or precipitation, so that lakes receiving groundwater inputs are more concentrated than lakes that do not.

With respect to our biological parameters, the data are as yet too preliminary to confirm patterns of trophic development. Among nutrients, total-nitrogen appears to increase during the earliest stages of lake development, reflecting perhaps the expansion of N-fixing alder in the terrestrial vegetation during the first few decades following deglaciation. This trend may be manifest in an increase in phytoplankton production during the first two centuries of the chronosequence.

This year's macrophyte survey points to a very striking relationship between lake alkalinity and the abundance of a number of higher aquatic plants, such as *Nuphar, Hippuris, Menyanthes,* and several species of *Potamogeton*. This relationship is probably due to the ability of different species to photosynthetically fix CO_2 or HCO_3^- from lakewater and is significant in lake ontogeny because of the loss of alkalinity with landscape maturation. Because macrophytes provide growth surfaces for other organisms and contribute heterogeneity to aquatic habitats, a macrophyte succession mediated by alkalinity changes has major implications for the biotic evolution of lakes in Glacier Bay.

Paleolimnology

The stratigraphy of diatoms in lake sediment cores can be used to reconstruct changes in water chemisty, as well as the availability of substrates such as macrophytes for algal growth. Fig. 5 shows the diatom stratigraphy of Lester #2, a 180-year-old moderately alkaline lake on Lester Island. The basal sediments are highly inorganic and contain a restricted diatom flora of three benthic taxa common in alkaline lakes. The dominance in these basal sediments of *Gyrosigma spencerii*, a large, heavily silicified taxon found in high-energy environments, probably reflects high turbidity resulting from unstable slopes in the newly deglaciated landscape. This

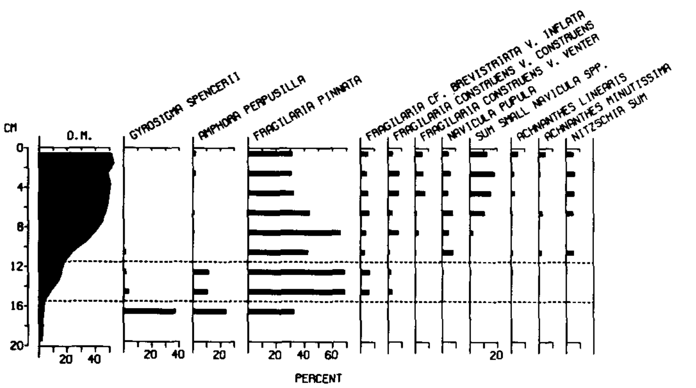

Fig. 5. Preliminary diatom analysis of a core from a 180-year-old lake on Lester Island; O.M. = % organic matter in dry sediment from loss-on-ignition.

species declines in abundance as the organic content of the sediment increases, a result of plant invasion and stabilization of the surrounding catchment. Subsequently, both benthic and epiphytic taxa characteristic of cicumneutral and alkaline waters invade and expand, including several *Fragilaria* and *Achnanthes* spp., *Navicula pupula, N. tantula, N. minima, N. seminulum, N. subatomides,* and *N. subrotundata.* This diversification of the flora undoubtedly reflects the proliferation of new habitats for diatom growth, particularly the invasion and expansion of macrophytes, such as *Potamogeton* spp. and *Equisetum.* Ultimately, we plan to use recently collected samples of modern diatom communities in Glacier Bay lakes as analogues in the interpretation of the core samples, permitting quantitative reconstruction of changes in water chemistry through time, especially trends in pH, alkalinity, and water color.

Discussion

The preliminary trends observed in this study allow us to speculate on properties of the land/water system that might cause limnological change over the long course of time. The impacts of vegetational succession, soil development, and hydrological change, all potential agents of lake ontogeny, cannot be observed directly because of the slow pace at which they proceed. However, their influence can be inferred by correlation of apparent trends in terrestrial and aquatic succession.

In the case of soil development, we have a fairly clear picture of carbonate loss, pH decline, and nitrogen increase during the first century of terrestrial succession in Glacier Bay (Crocker and Major 1955). Thus, the weathering of soluble minerals from upper soil horizons may be practically responsible for lakes becoming more dilute and acidic over time. Likewise, the steady accretion of an organic soil horizon no doubt contributes to a greater flux of organic acids that stain the waters of older lakes (Engstrom 1987). However, it is as yet unclear whether lake alkalinities actually decline over the same period of time (0-200 years) that initial soil development is thought to occur. Furthermore, while surficial catchment drainage may lose ionic strength because of weathering, groundwater at depth should be relatively unaffected by this process. Thus, lakes receiving even a moderate load of dissolved solids from subsurface flow should be slow to respond to terrestrial succession.

That essentially all of the older sites along the outer coast and on Pleasant Island (most in carbonate-rich terrain) are dilute and at least somewhat acidic implies that eventually groundwater inputs to lakes decrease over time, either in volume or in concentration. A decrease in groundwater flux could be caused by a long-term decline in recharge associated with soil development. Indurated soil horizons and thick accumulations of peat, which begin forming several hundred years after disturbance in Southeast Alaska (Ugolini and Mann 1979), could gradually inhibit internal soil drainage and transform groundwater recharge into surficial flow. Catchment drainage coursing through peat or weathered soil horizons would bear a much smaller load of dissolved solids than the groundwater it displaced, and lakes receiving these inputs would gradually become more dilute and acidic (Almendinger, this volume).

From this model on lake ontogeny, we could expect that individual lakes would follow different trajectories, depending on hydrologic and geologic settings. Lake basins in granitic terrain, for example, would likely begin with more dilute waters than basins in sedimentary rock and might become acidic more rapidly. On the other hand, groundwater inputs should buffer lakes from the immediate effects of soil development so the basins receiving groundwater discharge should change more slowly than lakes fed solely by surficial drainage and direct precipitation. In general, however, lake evolution in Glacier Bay can be viewed as a convergent process of progressive dilution and acidification.

At present, such trends can only be inferred for low elevation sites in Glacier Bay where organic-rich soils develop under coniferous vegetation. The cool, moist climate of Alaska's temperate rainforests offers an ideal setting for the edaphic changes embodied in this model of lake ontogeny. However, similar conditions exist throughout the boreal forest regions of North America and Europe, and the patterns of limnological change envisioned for Glacier Bay may thus apply to many of the lakes created by continental glaciation.

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